

# The binary merger channel for the progenitor of the fastest rotating O-type star VFTS102

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Accepted .... Received .....; in original form ....

## ABSTRACT

VFTS102 has a projected rotational velocity ( $>500 \text{ km s}^{-1}$ ) and would appear to be the fastest rotating O-type star. We show that its high rotational velocity could be understood within the framework of the binary merger. In the binary merger channel, the progenitor binary of VFTS102 would evolve into contact while two components are still on the main sequence, and then merge into a rapidly rotating single star. Employing Eggleton’s stellar evolution code, we performed binary stellar evolution calculations and mapped out the initial parameters of the progenitor of VFTS102 in the orbital period-mass ratio ( $P-q$ ) plane. We found that the progenitor binary of VFTS102 with initial mass ratio  $q_0 \lesssim 0.7$  should have an initial orbital period shorter than 3.76–4.25 days, while above this mass ratio it should have an initial orbital period shorter than 1.44–1.55 days. The progenitor of VFTS102 would evolve into contact during the rapid mass transfer phase or during the subsequent slow mass transfer phase, and might ultimately merge into a rapidly rotating massive star. In addition, we performed Monte Carlo simulations to investigate the binary merger channel. We estimated the fraction of binaries that would merge into single stars and the fraction of single stars that might be produced from the binary merger channel. It is found that about 8.7% of binaries would evolve into contact and merge into rapidly rotating single stars, and about 17.1% of single stars might be produced from the binary merger channel and should have similar properties to VFTS102. This suggests that the binary merger

channel might be one of the main channels for the formation of rapidly rotating massive stars like VFTS102.

**Key words:** instabilities – stars: early-type – stars: formation – stars: evolution – stars: rotation

## 1 INTRODUCTION

VFTS102 is a rapidly rotating O-type star in the 30 Doradus region of the Large Magellanic Cloud, and its projected rotational velocity is larger than  $500 \text{ km s}^{-1}$  and probably as large as  $600 \text{ km s}^{-1}$  (Dufton et al. 2011). It rotates more rapidly than any observed stars in recent large surveys (Martayan et al. 2006; Hunter et al. 2008, 2009) and would appear to be the most rapidly rotating massive star (Dufton et al. 2011). The rapidly rotating stars such as VFTS102 form an important class of objects in several respects. These stars could help us to study the rotational effects that are important, from star formation through to their deaths (Hunter et al. 2008). Fast rotation could change the lifetime and evolution of massive stars by rotationally induced mixing between the core and envelope (Heger & Langer 2000; Meynet & Maeder 2000), and produce enrichment of a number of different elements at the stellar surface (Hunter et al. 2009; Frischknecht et al. 2010; Potter, Tout & Eldridge 2012). The rotationally induced mixing were used to explain the variety of core collapse supernovae (Georgy et al. 2009). In addition, the rotating massive stars might be the progenitors of gamma-ray bursts through homogeneous evolution (Yoon & Langer 2005; Woosley & Heger 2006; Tout 2011).

Two channels for the formation of VFTS102 have been proposed in the past. The first channel is the mass transfer channel (Dufton et al. 2011). In this channel, VFTS102 might be the mass gainer and be spun up by a past episode of Roche lobe overflow (RLOF) in an interacting binary system (Packet 1981; Cantiello et al. 2007; Dufton et al. 2011). Dufton et al. (2011) suggested that VFTS102 became a runaway star after its companion exploded as a supernova. This channel could also explain that the radial velocity of VFTS102 differs by  $40 \text{ km s}^{-1}$  from the mean radial velocity for 30 Doradus. The second channel is the collision channel (Fryer & Heger 2005; Fujii, Saitoh & Portegies Zwart 2012). Fujii, Saitoh & Portegies Zwart (2012) proposed that VFTS102 had experienced a earlier collision, and then might be ejected from the cluster center. The fast rotation of VFTS102

might be the result of the collision with another star in the cluster center. In addition, VFTS102 might be born as rapid rotator (Huang, Gies & McSwain 2010; Brott et al. 2011) or its surface might spin up during the main sequence (MS) evolution because angular momentum was transported from the center to the stellar surface (Ekström et al. 2008).

From a binary evolution point of view, these formation channels are not complete. The binary merger might be another possible channel to produce the fastest rotating star VFTS102. In this channel, the initial detached binary would experience case A mass transfer and evolve into contact while two components are still on the MS, and then merge into a rapidly rotating single star (Webbink 1976; Jiang et al. 2010; de Mink, Langer & Izzard 2011; Langer 2012). It is well known that the fraction of massive stars that are members of a close binary is very large (Mason et al. 2009; Langer 2012). Sana et al. (2012) found that 20% of all stars born as O-type stars would merge as a result of case A mass transfer. In addition, the observations show that the massive contact binaries are relatively common, such as V606 Cen ( $P=1.495$  d Lorenz, Mayer, & Drechsel 1999) and TU Mus ( $P=1.387$  d Terrell et al. 2003; Qian et al. 2007), and  $\sim 5\%$  of O-type stars appear to be in contact with orbital periods of  $\sim 1-5.5$  days (Garmany, Conti & Massey 1980; Hilditch & Bell 1987; Eggleton 1996). These massive contact binaries might merge into single stars in a similar way as low-mass contact binaries, which might merge into single stars due to tidal instability when the spin angular momentum of the system is more than a third of its orbital angular momentum (Hut 1980; Rasio 1995; Li & Zhang 2006), or due to thermal instability when the primary attempts to cross the Hertzsprung gap (Webbink 1976). The merger of contact binaries are expected to result in single, massive stars (Chen & Han 2008; Tout 2011), which would be extremely rapidly rotating due to the orbital angular momentum of the binary systems (Cantiello et al. 2007; Jiang et al. 2010; de Mink, Langer & Izzard 2011; Langer 2012). Therefore, the binary merger might be a possible channel for the production of VFTS102.

The evolution of massive close binaries has been investigated by many authors, e.g. Podsiadlowski, Joss & Hsu (1992); Pols (1994); Wellstein, Langer & Braun (2001); Nelson & Eggleton (2001); de Mink, Pols & Hilditch (2007). Nelson & Eggleton (2001) calculated the case A binary evolution and constructed a large grid of models ( $0.8 \leq M_{10} \leq 50$ ). They mapped out the initial parameters in the mass ratio-orbital period plane of six subtypes of case A evolution. They suggested that three of these subtypes (AR, AS, AD) lead to contact while both components are on the MS. In case AR or AS, the secondary expands in response to the thermal time-scale mass transfer or the nuclear time-scale mass transfer from the primary

and fills its own Roche lobe. The system probably form a stable contact binary, and might ultimately merge into a single star. However, in case AD, the secondary cannot accrete all the proffered material transfer from the primary on the dynamical time-scale. This probably leads very quickly to a common envelope, spiral-in (Paczynski 1976; Hjellming & Webbink 1987; Ge et al. 2010), and coalescence on a quite short timescale (Nelson & Eggleton 2001; Jiang et al. 2012). Case AD might be common in the low mass binaries (Nelson & Eggleton 2001; Jiang et al. 2012), especially in those binaries with two M dwarf components observed by Becker et al. (2011) and Nefs et al. (2012). Few massive systems are classified as AD and most of massive contact systems are classified as AR or AS (Nelson & Eggleton 2001; de Mink, Pols & Hilditch 2007). Therefore, the investigation of the evolution of massive binaries in case AR and AS is important to understand the formation of massive contact binaries, and then the formation of the rapidly rotating stars such as VFTS102.

The purpose of this study is to investigate the binary merger channel for the progenitor of VFTS102 and to determine the detailed parameter range in which this channel produces VFTS102. Employing the Eggleton’s stellar evolution code, we construct a grid of binary models for metallicity  $Z = 0.01$  in Section 2 and 3, and then implement the results in a binary population synthesis study in Section 4. In Section 5, we give the discussion and conclusions.

## 2 BINARY EVOLUTION CALCULATIONS

In the binary merger channel for the progenitor of the fastest rotating O-type star VFTS102, the primary of the initial detached binary would fill its Roche lobe and transfer some of its mass to the secondary. The secondary expands in response to the mass transfer from the primary. This system would evolve into contact if the secondary fills its own Roche lobe when two components are still MS stars. These contact systems would ultimately merge into rotating stars due to the orbital angular momentum of the binary systems (Jiang et al. 2010; Langer 2012). Furthermore, if both components are MS stars in case A binaries, the merged stars would be MS stars and evolve in a similar way to a normal star with that mass (Chen & Han 2009; Langer 2012). Therefore, the merged stars with the same mass as VFTS102 might be similar to VFTS102.

There are some constraints on the progenitor of VFTS102 in the binary merger model. First, the detached binary, as the progenitor of VFTS102, should evolve into contact while

two component are still on the MS, which is largely determined by the initial period and mass ratio. Secondly, the total mass of the progenitor binary should be larger than or equal to the mass of VFTS102, which depends on the mass loss during the evolution and the merger process. The current mass of VFTS102 is approximately  $25 M_{\odot}$  (Dufton et al. 2011). In this study, we do not consider the mass loss during the evolution and merger process and assume that the binary system as the progenitor of VFTS102 has total mass  $\sim 24.5 - 25.5 M_{\odot}$ .

The merger process is complicated and the merger physics is still uncertain. Here, we adopt the following assumptions: (i) the binary systems merge immediately once both MS components fill their Roche lobes; (ii) the merged stars are homogeneously mixed; (iii) the system mass is conserved. The merged timescale (i.e. the time from a binary contact to merger) for massive contact binaries has remained unclear and we only adopt a simple assumption that the merger is instantaneous. As the components of contact binaries rotate rapidly during the merger process, the merged stars would be efficiently mixed. These merged stars might also undergo rotationally induced mixing during the subsequent evolution (Langer 2012), which is important in the evolution of massive stars (e.g. Heger & Langer 2000; Maeder & Meynet 2000; Howarth & Smith 2001). Therefore, it is reasonable to assume that the merged stars are homogeneously mixed. We roughly assume that the mass is conservative during the merger process. In fact, the binary systems might lose high angular momentum material during the merger process and the merged stars might rotate at subcritical rotation velocities (Langer 2012). The second and the third assumptions were often adopted in the study of the formation of blue stragglers by the binary merger (e.g. Andronov, Pinsonneault & Terndrup 2006; Chen & Han 2008, 2009).

To determine whether the detached binary evolves into contact when two component are still MS stars, it is necessary to perform detailed binary evolution calculations. Here we use Eggleton's stellar evolution code originally developed by Eggleton (1971, 1972); Eggleton, Faulkner & Flannery (1973). This code has been updated with the latest input physics during the last four decades (e.g. Han, Podsiadlowski & Eggleton 1994; Pols et al. 1995, 1998; Nelson & Eggleton 2001; Eggleton & Kiseleva-Eggleton 2002). We calculated our models with metallicity  $Z = 0.01$  (hydrogen abundance  $X = 0.73$  and Helium abundance  $Y = 0.26$ ), which is close to the chemical composition of Large Magellanic Cloud ( $Z = 0.008$ ). The mass transfer is determined to be dynamic when the mass-transfer is greater than  $10M/t_{\text{KH}}$ , where  $t_{\text{KH}}$  is the thermal or Kelvin-Helmholtz timescale (Nelson & Eggleton

2001). We construct a grid of stellar evolutionary models that covers the following ranges of initial primary mass  $M_{10}$  and initial mass ratio ( $q_0 = M_{20}/M_{10}$ ):

$$\log M_{10} = 1.10, 1.15, \dots, 1.35, \quad (1)$$

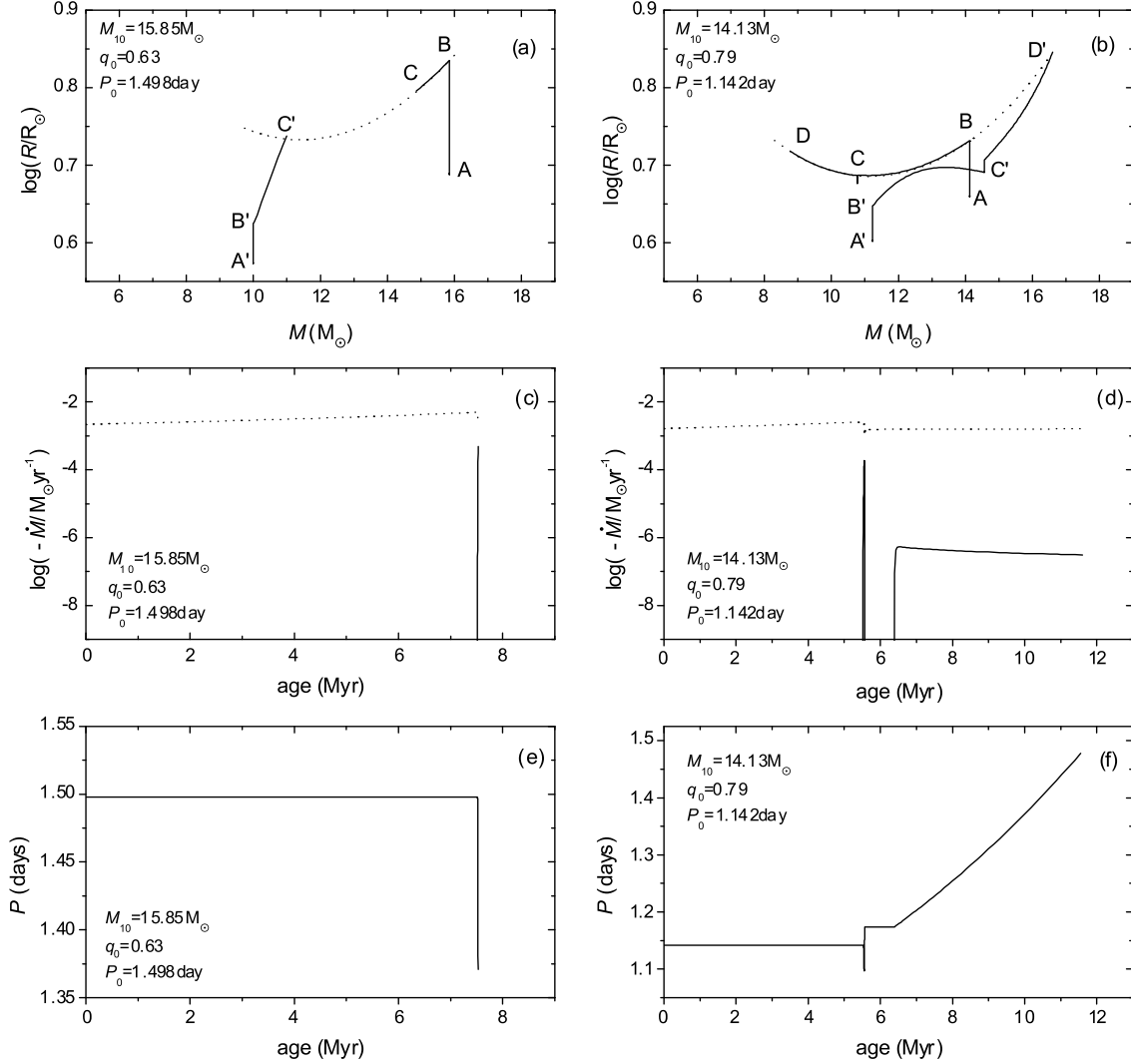
$$\log(1/q_0) = 0.004, 0.05, 0.10, \dots, 0.95, \quad (2)$$

$$\log(P_0/P_{\text{ZAMS}}) = 0.05, 0.10, \dots, 0.75, \quad (3)$$

where  $P_{\text{ZAMS}}$  is the period at which the initially more massive component would just fill its Roche lobe on the zero-age MS (Nelson & Eggleton 2001). The orbits are assumed to be circular. A binary is expected to become circularized during the RLOF by the tidal force on a timescale which is much smaller than the nuclear timescale (Wang, Li & Han 2010). We assume that both total mass and orbital angular momentum are conserved in the evolution of the binaries. If the loss of the total mass and orbital angular momentum is considered, the orbit of the initial detached binaries would quickly shrink. More detached binaries with longer period would evolve into RLOF and contact, which could not evolve into contact in the conservation evolution.

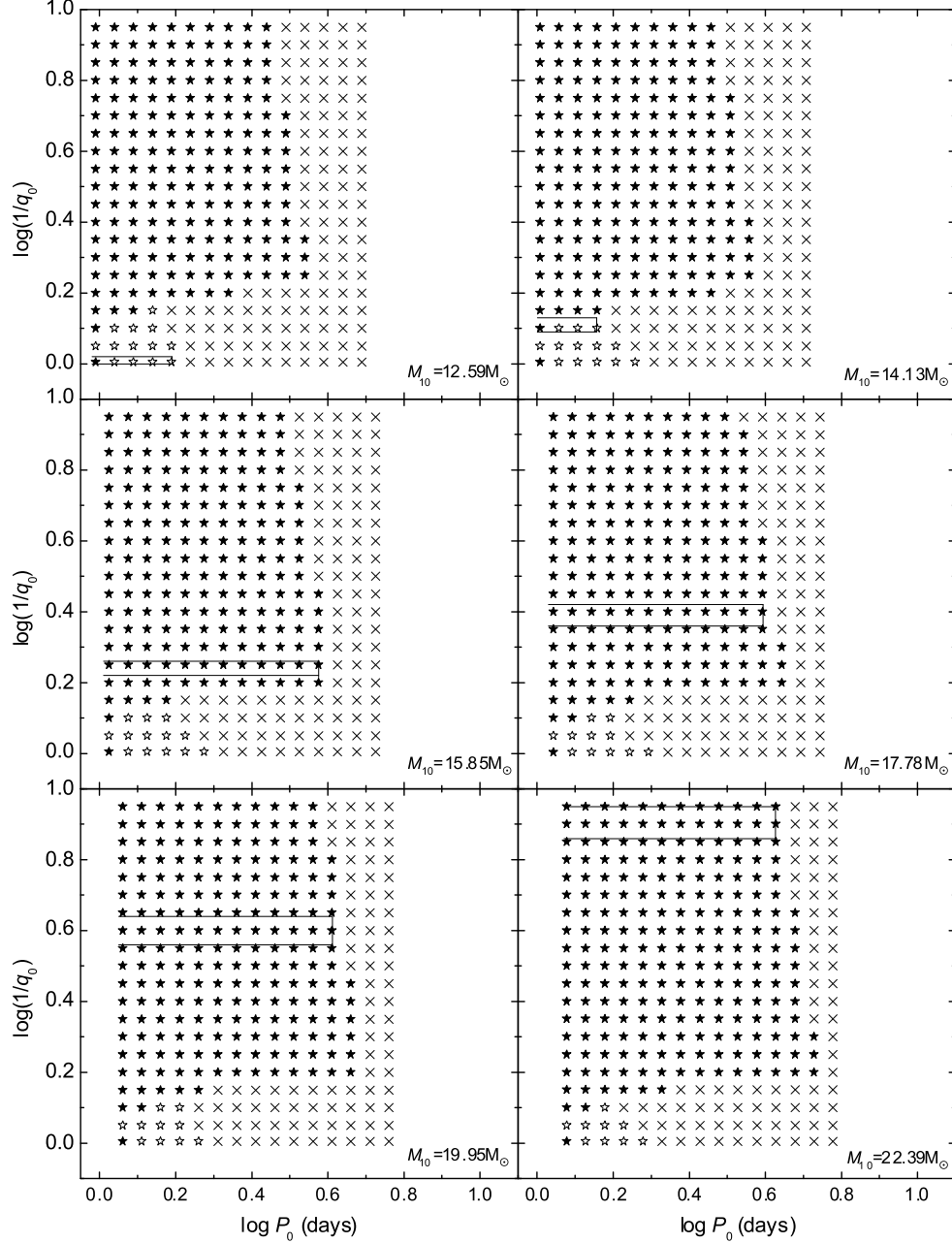
### 3 BINARY EVOLUTION RESULTS

In Fig. 1, we present two representative examples of our binary evolution calculations that could evolve into contact while two components are still on the MS. It shows the evolutionary track in the radius-mass diagram, the mass-transfer rate and the evolution of the orbital period. Figs 1(a), (c) and (e) represent the evolution of a binary system with an initial mass of the primary of  $\log M_{10} = 1.20$  ( $M_{10} = 15.85 M_{\odot}$ ), an initial mass ratio of  $\log(1/q_0) = 0.20$  ( $q_0 = 0.63$ ) and an initial orbital period of  $\log(P_0/P_{\text{ZAMS}}) = 0.2$  ( $P_0 = 1.498$  d). The components start to evolve from point A and A', and the primary fills its Roche lobe on the MS at point B which results in case A RLOF (BC) as shown in Fig. 1(a). The secondary expands in response to the mass transfer (B'C') and fills its Roche lobe at point C'. This system evolves into contact shortly after the start of RLOF. The mass-transfer rate from the primary to the secondary is not greater than  $10M/t_{\text{KH}}$  as shown in Fig.1(c). Therefore, the mass transfer is on a thermal time-scale and this case of binary evolution is classed as case AR (Nelson & Eggleton 2001). Fig. 1(e) shows that the orbital period of the system decreases from 1.498 to 1.37 d during the mass transfer phase because the mass is transferred from the massive component to the low-mass component.



**Figure 1.** Two examples of binary evolution calculations. In panels (a) and (b), solid curves show the evolutionary tracks in the radius-mass diagram for the primaries (ABC and ABCD) and the secondaries (A'B'C' and A'B'C'D'), and the dotted curves represent the Roche lobe. The components start at point A or A', and evolve along curves until both components fills their Roche lobe at point C and C', or D and D'. In panels (c) and (d), the solid curves show the mass transfer rates and the dotted curves represent  $10M/t_{\text{KH}}$  that is used to determined whether the mass transfer is dynamic. The evolution of orbital period is shown as solid curves in panels (e) and (f).

Figs 1(b), (d) and (f) show another example for an initial mass of the primary of  $\log M_{10} = 1.15$  ( $M_{10} = 14.13 M_{\odot}$ ), an initial mass ratio of  $\log(1/q_0) = 0.10$  ( $q_0 = 0.79$ ) and an initial orbital period of  $\log(P_0/P_{\text{ZAMS}}) = 0.1$  ( $P_0 = 1.142 \text{ d}$ ). The main difference between this example and the previous one is that the secondary fills its own Roche lobe, not during the rapid mass transfer phase (B'C'), but during the subsequent slow mass transfer phase (C'D') as shown in Fig. 1(b). This case of binary evolution is identified as case AS (Nelson & Eggleton 2001). In this case, as shown in Fig. 1(d), the mass transfer rate is about  $1.8 \times 10^{-4} M_{\odot}/\text{yr}$  during the rapid mass transfer phase (BC) and about  $5 \times 10^{-7} M_{\odot}/\text{yr}$  during the slow mass



**Figure 2.** The outcomes of binary evolution calculations in the initial orbital period–mass ratio ( $\log P_0$ ,  $\log(1/q_0)$ ) plane while both components are still MS stars, where  $P_0$  is the initial orbital period and  $q_0$  is the initial mass ratio (for different initial primaries as indicated in each panel). Filled stars show the systems that evolve into contact during the rapid mass transfer phase while both components are on the MS (case AR). Open stars show the systems that evolve into contact during the slow mass transfer phase (case AS). Crosses indicate the systems that could not evolve into contact while two components are still on MS. Solid lines show the boundaries (without left boundaries) for the initial parameters for which might be the progenitor of VFTS102.

transfer phase (CD). The orbital period of this system first decreases from 1.142 to 1.097d, and then increases to 1.478d after the mass ratio is reversed as shown in Fig. 1(f).

Fig. 2 summarizes the outcomes of binary evolution calculations in the initial orbital period–mass ratio ( $\log P_0$ ,  $\log(1/q_0)$ ) plane while both components are still MS stars. Filled stars show the systems that evolve into contact during the rapid mass transfer phase while



both components are on the MS (case AR). Open stars show the systems that evolve into contact during the slow mass transfer phase (case AS). Crosses indicate the systems that could not evolve into contact while two components are still on MS. We also present the boundaries (solid lines) for the initial parameters for which might be the progenitor of VFTS102. The right boundaries are set by the condition that the system could evolve into contact while two components are still on the MS. The upper and lower boundaries are caused by the constraint of the mass of VFTS102. The left boundaries are not plotted in Fig. 2, which are set by the period ( $P_{\text{ZAMS}}$ ) at which the initially more massive component would just fill its Roche lobe on the zero-age MS. It is seen from Fig. 2 that the progenitor binary of VFTS102 with  $q_0 \lesssim 0.7$  ( $\log q_0 \gtrsim 0.2$ ) should have an initial orbital period shorter than 3.76 – 4.25 days and they would evolve into contact during the rapid mass transfer phase. The progenitor binary of VFTS102 with  $q_0 > 0.7$  ( $\log q_0 < 0.2$ ) should have an initial orbital period shorter than 1.44 – 1.55 days and they would evolve into contact during the rapid or slow mass transfer phase.

#### 4 BINARY POPULATION SYNTHESIS

We have performed a series of detailed Monte Carlo simulations to investigate the binary merger channel. In each simulation, we follow the evolution of 100 million sample binaries (very wide binaries are actually single stars) according to grids of stellar models of metallicity  $Z = 0.01$  and the evolution channels described above. We adopt the following input for the simulations: the initial mass function (IMF) of the primaries, the initial mass-ratio distribution, and the distribution of initial orbital separations (e.g. Han et al. 2002, 2003; Liu 2009; Wang, Li & Han 2010):

(i) We use a simple approximation to the IMF of Miller & Scalo (1979) and the mass of the primary is generated using a formula of Eggleton, Tout & Fitchett (1989),

$$M_{10} = \frac{0.19X}{(1-X)^{0.75} + 0.032(1-X)^{0.25}}, \quad (4)$$

where  $X$  is a random number uniformly distributed between 0 and 1. The study of IMF by Kroupa, Tout & Gilmore (1993) supports this IMF.

(ii) We take a uniform mass-ratio distribution (Set 1),

$$n(q_0) = 1, \quad 0 \leq q_0 \leq 1 \quad (5)$$

Table 1. The results of the binary population synthesis for the binary merger channel.

Set	$n(q_0)$	$N_m$	$N_b$	$f_b$	$N_s$	$f_s$
1	Uniform	1006	11581	8.7%	4875	17.1%
2	Rising	787	10834	7.3%	4223	15.7%
3	Uncorrelated	52	7559	0.7%	4830	1.1%

Columns: Set-name of different simulation set;  $n(q_0)$ -the distribution of the mass ratio distribution;  $N_m$ -the number of binaries with total mass  $\sim 24.5 - 25.5 M_\odot$  that would merge into single stars;  $N_b$ -the number of the initial binaries with total mass  $\sim 24.5 - 25.5 M_\odot$ ;  $f_b$ -the fraction of binaries that would merge into single stars ( $f_b = N_m/N_b$ );  $N_s$ -the number of the initial single stars with mass  $\sim 24.5 - 25.5 M_\odot$ ;  $f_s$ -the fraction of single stars that might be produced from the binary merger channel ( $f_s = N_m/(N_m + N_s)$ ).

where  $q_0 = M_{20}/M_{10}$  (Mazeh et al. 1992; Goldberg & Mazeh 1994). In order to study the influence of the mass ratio distribution, we also take a rising mass ratio distribution (Set 2)

$$n(q_0) = 2q_0, \quad 0 \leq q_0 \leq 1 \quad (6)$$

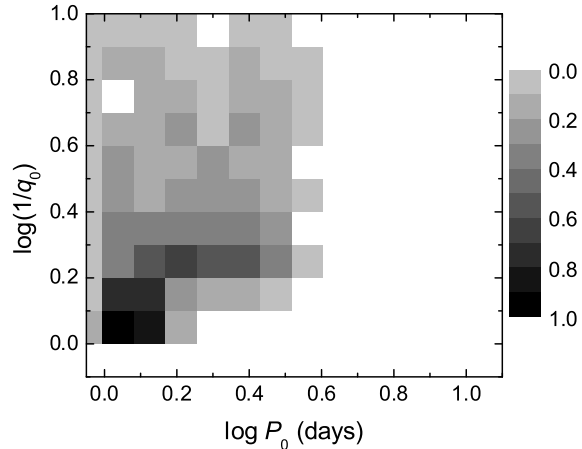
and an alternative mass-ratio distribution where both components are chosen randomly and independently from the same IMF (Set 3).

(iii) We assume that all stars are members of binary systems and that the distribution of separations is constant in  $\log a$  for wide binaries, where  $a$  is the orbital separation and falls off smoothly at small separation

$$an(a) = \begin{cases} \alpha_{\text{sep}} \left(\frac{a}{a_0}\right)^m, & a \leq a_0, \\ \alpha_{\text{sep}}, & a_0 < a < a_1, \end{cases} \quad (7)$$

where  $\alpha_{\text{sep}} \approx 0.070$ ,  $a_0 = 10 R_\odot$ ,  $a_1 = 5.75 \times 10^6 R_\odot = 0.13 \text{ pc}$ , and  $m \approx 1.2$ . This distribution implies that the numbers of wide binary systems per logarithmic interval are equal, and that about 50% of stellar systems have orbital periods less than 100 yr (Han, Podsiadlowski & Eggleton 1995). A circular orbit is assumed for all binaries.

The results of the binary population synthesis are shown in Table 1 for three sets of simulations.  $N_m$ ,  $N_b$  and  $N_s$  are the number of binaries that would merge into single stars, the initial binaries and the initial single stars, all of which are in the range of mass (or total mass for the binaries) from 24.5 to 25.5  $M_\odot$ .  $f_b$  is the fraction of binaries that would merge into single stars, and  $f_s$  is the fraction of single stars that might be produced from the binary merger channel, where  $f_b = N_m/N_b$ , and  $f_s = N_m/(N_m + N_s)$ . Set 1 is our standard model for the binary merger channel and we vary the mass ratio distribution in the other sets to examine its influence on the final results. The simulation for the binary merger channel gives  $f_b \sim 8.7\%$  and  $f_s \sim 17.1\%$  according to our standard model (Set 1). This suggests that about 8.7% of binaries would evolve into contact and merge into rapidly rotating single stars, and about 17.1% of single stars might be produced from the binary merger channel and should



**Figure 3.** The relative number distribution of the progenitor of VFTS102 in the initial orbital period–mass ratio ( $\log P_0$ ,  $\log(1/q_0)$ ) plane.

have similar properties to VFTS102. The simulation for a rising mass-ratio distribution (Set 2) gives  $f_b \sim 7.3\%$  and  $f_s \sim 15.7\%$ , which are close to the results in Set 1. If we adopt a mass-ratio distribution with uncorrelated binary components, two fractions ( $f_b \sim 0.7\%$  and  $f_s \sim 1.1\%$ ) are much lower than the results in Set 1. This is because most of binary systems have too small a mass ratio ( $q_0$ ) to locate in the region of the progenitor of VFTS102 for different initial primaries.

Fig. 3 shows the relative number distribution of the progenitor of VFTS102 in the initial orbital period–mass ratio plane (Set 1). It is found that the distribution of the progenitor of VFTS102 increases with decreasing orbital period and increasing mass ratio ( $q_0$ ). This suggests that VFTS102 mainly comes from the binary with short period and large mass ratio. The most likely progenitor binary of VFTS102 might have an orbital period  $P_0 < 1.5$  d and a mass ratio  $q_0 > 0.63$ , which roughly corresponds to a binary with a primary mass ( $M_{10} \sim 12.5 - 15 M_\odot$ ) according to Fig. 2. This is mainly because the number of initial binaries increases with the decreasing primary mass according to the IMF of the primaries, and more systems with low-mass primaries could be located in the production region of VFTS102.

## 5 DISCUSSION AND CONCLUSIONS

In this paper, we investigated the binary merger channel for the progenitor of the fastest rotating O-type star VFTS102. We carried out detailed binary evolution calculations and obtained the initial parameters of the progenitor of VFTS102 in the orbital period-mass ratio plane. By performing Monte Carlo simulations, we estimated the fraction of binaries

that would merge into single stars and the fraction of single stars that might be produced from the binary merger channel.

Duften et al. (2011) proposed that VFTS102 originated from a binary system, and the mass transfer from its component resulted in the fast rotation of VFTS102. They suggested that the subsequent supernova explosion of its component kicked both components and led to an anomalous radial velocity for VFTS102. We showed that the fast rotation of VFTS102 could be understood within the framework of the binary merger channel. In this channel, a detached binary evolves into contact and then merges into a rapidly rotating single star due to the orbital angular momentum of the binary systems (Webbink 1976; Jiang et al. 2010; de Mink, Langer & Izzard 2011; Langer 2012). The anomalous radial velocity for VFTS102 might be produced by the progenitor binary, which might be a binary dynamically ejected from a cluster (de Wit et al. 2005; Eldridge, Langer & Tout 2011; Gvaramadze & Gualandris 2011).

We mapped out the initial parameters of the progenitor of VFTS102 in the binary merger channel. Our results are very similar to those given by Pols (1994). He showed the parameter space of initial mass ratio and orbital period for the systems with  $16 M_{\odot}$ , which was explored for the formation of contact binaries. By performing Monte Carlo simulations, we found that the most likely progenitor of VFTS102 might have a primary mass  $M_{10} \sim 12.5 - 15 M_{\odot}$ , a mass ratio  $q_0 > 0.63$  and an orbital period  $P_0 < 1.5$  d.

According to the work of Podsiadlowski, Joss & Hsu (1992), the fraction of binaries that experience case A and merge is about 14.8%, which is larger than 8.7% found in this study. This is because they assumed that case A mass transfer always leads to a merger of two component, in which some of binaries would reach contact while one or both components evolve past the terminal MS (Nelson & Eggleton 2001), and these binaries are not considered in our study. In addition, Langer (2012) suggested that up to 10% or more of the stars would be merger remnants, which is close to the result of our study (17.1%). Therefore, the binary merger channel might be one of the main channels for the production of rapidly rotating star like VFTS102 and it is necessary to consider this channel for the study of the formation of rapidly rotating stars.

Tylenda et al. (2011) showed the direct observation evidence that contact binaries indeed merge into a single object from the identification of V1309 Sco. The observations also show some possible progenitor of VFTS102-like objects that are short-period, massive semi-detached or contact binaries, such as V Pup ( $P=1.45$  d Andersen et al. 1983), IU Aur

( $P=1.811$  d Harries, Hilditch & Hill 1998), V606 Cen ( $P=1.495$  d Lorenz, Mayer, & Drechsel 1999) and TU Mus ( $P=1.387$  d Terrell et al. 2003; Qian et al. 2007). In addition, some mass should be lost from binary systems during the merger process to carry away the excess angular momentum (Jiang et al. 2010; Langer 2012), which might form circumstellar material or a circumstellar disc. This could explain the observation that VFTS102 has circumstellar material found by Dufton et al. (2011).

In this paper, we investigated the binary merger channel for the progenitor of VFTS102 without considering the mass loss during the evolution and merger phase. However, the mass loss is an important parameter in the evolution, the mass transfer phase and the merger phase of massive binaries, which needs to be considered in the future study. In addition, the merger process of the binaries and the evolution of the merger stars are still uncertain and need to be investigated further.

## ACKNOWLEDGEMENTS

It is a pleasure to thank the referee, Professor Ian Howarth, for his valuable suggestions and comments, which improve the paper greatly. This work was supported by the Chinese Natural Science Foundation (10773026, 10821061, 11073049, 2007CB815406, 11033008 and 11103073), the Foundation of Chinese Academy of Sciences (KJCX2-YW-T24) and the Western Light Youth Project.

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